VOLUME 78 SEPARATE No. 134

# PROCEEDINGS

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# SOLUTION OF AN HYDRAULIC PROBLEM BY ANALOG COMPUTER

By R. E. Glover, M. ASCE, D. J. Herbert, and C. R. Daum

HYDRAULICS DIVISION



**Headquarters of the Society**
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AMERICAN SOCIETY OF CIVIL ENGINEERS

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PAPERS

# SOLUTION OF AN HYDRAULIC PROBLEM BY ANALOG COMPUTER

By R. E. Glover,[1] M. ASCE, D. J. Hebert,[2] and C. R. Daum[3]

Synopsis

This paper discusses the general conditions of the problem of flow distribution in a network of estuarine channels to which an analog computer model was applied. After developing the analog requirements, the model is described, with emphasis on the electronic circuit that provides the required square-law resistance. The equations correlating electrical and hydraulic quantities are developed from the basic electrical and hydraulic relationships. Finally, the methods by which the required boundary conditions were duplicated are discussed.

## Introduction

The Delta area of California is a roughly triangular tract of land lying just to the east of Suisun Bay. This area, extending for a distance of about 50 miles north and south with a maximum width of about 25 miles, was originally a marsh with a network of channels threading through it. At the present time this area is agricultural land which has been reclaimed from the marshes by constructing dikes along the old channels to inclose areas that can be pumped out and farmed.

The Delta is traversed by the Sacramento River, entering from the north, by the San Joaquin River, entering from the south, and by the north and south forks of the Mokelumne River that come in from the east. The old network of channels, effectively preserved and stabilized by the process of reclamation, still carries the flow of these streams through the Delta.

Tides coming into San Francisco Bay from the Pacific Ocean propagate themselves through Suisun Bay and enter the Delta channels. Since the tidal currents generally exceed the currents resulting from stream flow, the direction

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Note.—Written comments are invited for publication; the last discussion should be submitted by December 1, 1952.

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of flow in the channels is periodically reversed and the resulting movement and mixing of fresh and saline waters provides a mechanism capable of propagating ocean salinity into the Delta channels. The salinity encroachment is held in check by stream flow that tends to flush the salinity out of the channels. In times of flood the salinity is driven back but in times of low stream flow the tidal ebb and flow succeeds in carrying some salt water into the channels.

Construction of Shasta Dam on the upper Sacramento River has made available a water supply intended for use on some of the lands in the San Joaquin Valley. To supply this demand, the Tracy pumping plant will lift water out of the channels at the south end of the Delta. This water must be brought across the Delta through its channels.

The problem to be solved is how to bring the Sacramento River water across the Delta to the San Joaquin side while maintaining a pattern of flow in the channels which will hold the intrusion of ocean salinity in check and thereby permit the transfer to be made without danger of contamination.

## Reasons for Use of an Analog

With the Tracy pumps in operation, it will be necessary to increase the natural transfer of water from the Sacramento channel to the San Joaquin channel in order to replenish the water supply of the southern part of the Delta

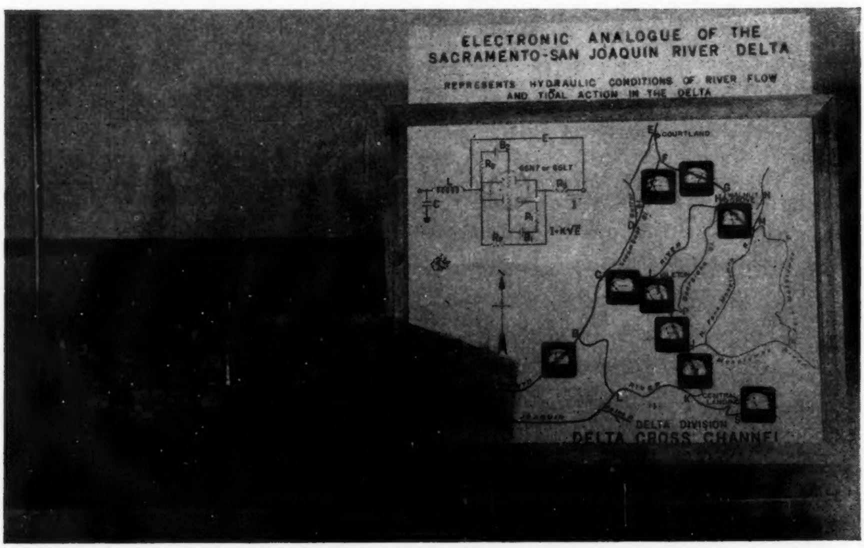


Fig. 1.—External Appearance of Electronic Analog

and thereby maintain a proper balance of flow. A tidal phase difference exists at one of the sites where a channel could be cut through to increase the transfer, and since gates would be necessary in any case for protection during floods, it would be possible to open the gates when the tidal currents were favorable and to

close them when the currents were adverse to increase the net flow. Good progress had previously been made for estimating flow patterns by model testing and by use of the procedure of Hardy Cross,[4] Hon. M. ASCE, but the complexities introduced by the tidal factor made it desirable to seek some new method of solution.

The electronic analog computer, built to expedite these computations, was successful for this purpose. The appearance of the completed analog is shown in Fig. 1.

## Design Requirements

In order to solve the Delta problem, it was required that the analog be able to reproduce the square-law relation between friction and velocity that is characteristic of fluid flow. In addition, it was required to represent the wave

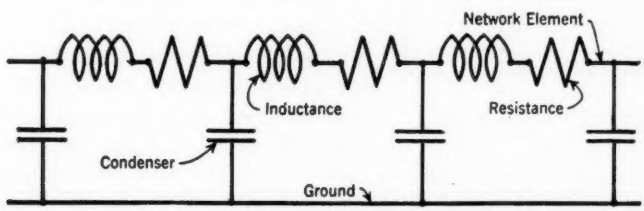


Fig. 2.—Basic Analog Circuit

motion associated with the tides. To do this, the factors of inertia and of storage resulting from water level changes had to be accounted for. The electrical factors employed in the analog to represent the hydraulic factors are as follows:

| Hydraulic | Electrical |
|---|---|
| Quantity of flow | Current |
| Water surface elevations | Voltage |
| Inertia | Inductance |
| Storage | Capacity |
| Frictional drag | Resistance |
| Time | Time |

## Description of the Analog

The analog is designed on the basis of circuits of the type shown in Fig. 2. The inductances are air-cored coils of commercial types or were wound as required. The condensers are commercial units of the paper or mica type. In the large channels having very low frictional resistance, linear resistors were used with appropriate average values for the currents flowing. In the smaller channels, however, it was necessary to use a type of square-law resistor, obtained by taking advantage of certain vacuum tube characteristics that have approximately the required form of variation. These tubes were used with resistors in parallel and in series to obtain the desired characteristic. A biasing

[4] "Analysis of Flow in Networks of Conduits or Conductors," by Hardy Cross, *Bulletin No. 286*, Univ. of Illinois Eng. Experiment Station, Urbana, Ill., November, 1936.

voltage was also required in this adjustment. The circuit used in such cases is shown in Fig. 3.

A dual triode tube with sections connected in parallel, opposing, is used to permit current to flow in either direction. This type of resistor is not wholly satisfactory since the tubes show variations that make it necessary to adjust each section separately. The current carrying capacity is restricted within narrow limits, and it is necessary, therefore, to design the analog around these elements. Net current flows were read on direct current milliammeters and tidal amplitudes and phase differences were read on a cathode-ray oscilloscope. The gate keeper was represented by a rectifier circuit that was also found to have some shortcomings near the zero point, introducing an effect analogous to gate leakage. In spite of these minor difficulties, the analog operates in a very satisfactory manner. Some idea of the speed with which the device works may be obtained from the fact that the analog runs through about 500 days of actual tidal changes in each second of operating time.

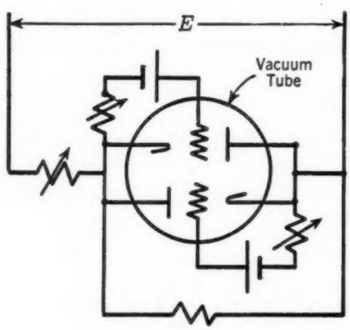


FIG. 3.—SQUARE-LAW RESISTOR

## BASIC EQUATIONS

In setting up the correlation equations, the electrical circuits were assumed to have their resistance, inductance, and capacity uniformly distributed along their length. In practice, these elements and the square-law resistances were lumped. The inertia and storage factors were considered together, and the resistances were considered separately.

A longitudinal section of a stream channel is shown in Fig. 4. The shaded element in Fig. 4 represents a lamina of width $b_w$, depth $H$, and length $dx$. For analytical purposes the actual channel is assimilated to a uniform rectangular channel that has the same top width and cross-sectional area as the actual channel. As stated previously, frictional forces are not introduced into the dynamical equations, but are treated separately. Since $x$ represents a distance measured along the stream from some fixed point on the bank, the planes

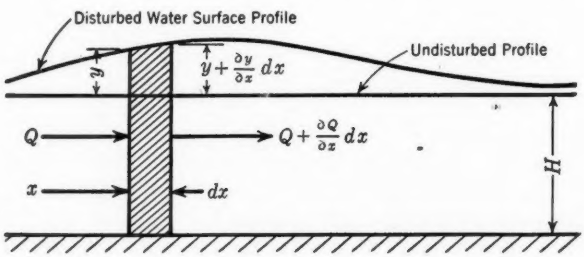


FIG. 4.—LONGITUDINAL SECTION OF A CHANNEL

defined by $x$ and $x + dx$ do not change position with time. It is assumed that $y$, the surface elevation above sea level, is small compared to $H$, the depth of the stream.

The continuity condition requires that, if the quantities of water flowing through the planes $x$ and $x + dx$ differ, the surface elevation must rise or fall as required to accommodate the changes of volume. If small quantities are neglected, this requirement is expressed by the equation:

$$b_w \, dx \frac{\partial y}{\partial t} = +Q - \left(Q + \frac{\partial Q}{\partial x} dx\right) \quad \ldots\ldots (1)$$

in which $t$ represents time and $Q$ represents flow. If a surface gradient $\partial y/\partial x$ is present, the water depth on one side of the lamina will be greater than on the other side by the amount $(\partial y/\partial x)\, dx$ and the additional pressure resulting from this head differential will cause the water within the lamina to be accelerated. Thus, the requirements of Newton's law are expressed to a first order of approximation by

$$\frac{\gamma \, b_w H}{g} dx \frac{\partial}{\partial t}\left(\frac{Q}{b_w H}\right) = -\gamma \, b_w H \frac{\partial y}{\partial x} dx \quad \ldots\ldots (2)$$

in which $\gamma$ represents the weight of water per unit volume and $g$ represents the acceleration of gravity. Eqs. 1 and 2 can be simplified by cancelling common terms and collecting. Then the equation of continuity becomes

$$\frac{\partial Q}{\partial x} + \frac{b_w \partial y}{\partial t} = 0 \quad \ldots\ldots (3)$$

and Newton's law takes the form:

$$\frac{\partial y}{\partial x} + \frac{1}{g H b_w} \frac{\partial Q}{\partial t} = 0 \quad \ldots\ldots (4)$$

It is of interest to note that if $Q$ is eliminated from Eqs. 3 and 4 the wave equation is obtained,

$$\frac{\partial^2 y}{\partial x^2} = \frac{1}{g H} \frac{\partial^2 y}{\partial t^2} \quad \ldots\ldots (5)$$

The relation between flow and gradient for the hydraulic channel can be expressed in the form:

$$Q = M \sqrt{\frac{\partial y}{\partial x}} \quad \ldots\ldots (6)$$

in which $M$ is a constant of the channel specifying its flow resistance. Eq. 6 may be recognized as a form of the Chezy formula. In the electrical circuits let $C$ represent the capacity per unit length of circuit; $E$ the potential with respect to ground; $I$ the current; $K$ a constant applying to a circuit; $r$ the resistance per unit length of circuit; $\eta$ the time in the analog; $\lambda$ the inductance per unit length of circuit; and $\xi$ the distance along a circuit.

Then, the equations for the idealized electrical circuits[5] that correspond to Eqs. 3 and 4 for the hydraulic channels are

$$\frac{\partial I}{\partial \xi} + C\frac{\partial E}{\partial \eta} = 0 \qquad (7)$$

$$\frac{\partial E}{\partial \xi} + \lambda\frac{\partial I}{\partial \eta} = 0 \qquad (8)$$

From Eqs. 7 and 8, there is obtained, on elimination of $I$,

$$\frac{\partial^2 E}{\partial \xi^2} = \lambda\, C\frac{\partial^2 E}{\partial \eta^2} \qquad (9)$$

For the circuits provided with an electronic resistor to represent hydraulic resistances of the type expressed by Eq. 6

$$I = K\sqrt{\frac{\partial E}{\partial \xi}} \qquad (10)$$

or, if the circuit has a linear resistance,

$$I = \frac{1}{r}\frac{\partial E}{\partial \xi} \qquad (11)$$

## Correlation Equations

The electronic analog operates at a frequency of 1,000 cycles per sec. The sinusoidal variations imposed on the analog approximately represent tidal oscillations having a frequency of about 2 cycles per day. The correlation equations that were found suitable for use with the available electrical components are as follows:

$$y = 0.1\, E \qquad (12a)$$

$$Q = 10{,}000{,}000\, I \qquad (12b)$$

$$x = 10{,}000\, \xi \qquad (12c)$$

$$t = 45{,}000{,}000\, \eta \qquad (12d)$$

Other applications would, of course, require other constants. An analogous electrical quantity is obtained by substituting the foregoing relations into the hydraulic equations. For example, Eq. 6, on substitution becomes

$$10{,}000{,}000\, I = M\sqrt{\frac{0.1\, \partial E}{10{,}000\, \partial \xi}} \qquad (13a)$$

or

$$I = \frac{M}{3.2 \times 10^9}\sqrt{\frac{\partial E}{\partial \xi}} \qquad (13b)$$

[5] "The Theory of Sound," by Lord Rayleigh, Dover Publications, London, England, 1945, Vol. 1, p. 467, paragraph 235.

Then, the quantity $\frac{M}{3.2 \times 10^9}$ is the $K$-value in Eq. 10. By this choice of constants the electrical circuit is given resistance characteristics that are analogous to the friction in the corresponding hydraulic channel. The other relations are treated in a similar way.

## Boundary Conditions

To account for the stream flow it was necessary to introduce direct currents of specified amounts at certain points in the analog and to take them out at certain other points. In general, the currents fed into the network represent river flows entering the Delta area, while currents leaving the network represent the draft of the Tracy pumps and the flow from the Delta area into Suisun Bay. To simulate these currents, voltages of controllable magnitude were introduced between the network and the ground wire (see Fig. 2). Control of the currents was obtained by variable resistors located at the points at which the currents enter and leave the network.

The tides were represented by alternating voltages of specified magnitude applied between the network and the ground wire at the point on the analog representing the entrance to Suisun Bay. A blocking condenser was used here to prevent the flow of direct current through the transformer windings. The actual tides occurring at this point vary somewhat from day to day because of varying phase relations between the lunar and solar components. In the analog, these tidal variations were replaced by a single sinusoidal variation of average amplitude. The connections arranged for introducing the direct currents representing stream flow would permit the alternating currents representing the tides to pass into the ground wire at other points than that representing the entrance to Suisun Bay. Since this would introduce errors, inductive blocking impedances were placed in the direct current circuit wherever necessary to confine the alternating currents to the proper network circuits. At points where stream channels continued beyond the area represented by the analog, lumped impedances were introuced in the circuit to represent those portions beyond the analog area. In most cases these impedances were determined by trial, so that known tidal behavior would be properly represented.

In order to protect the direct current meters from loss of field caused by the alternating current components, these meters were shunted by condensers having impedances to alternating current that were low compared to the resistance of the meter.

## Conclusions

An analog of the type described in this paper is an effective means of expediting the work of finding flow distribution patterns in a network of channels. It is particularly effective when tidal effects must also be included in addition to gravity flows. The results obtained have checked well with those obtained by other means.

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